IMPACT OF LOAD VARIATIONS ON THE STAGNATION OF NESTED STAINLESS STEEL AND COPPER Z PINCHES *

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Abstract

A variety of wire array experiments the last few years at the 20 MA Z Accelerator have been performed to assess the impact of initial load mass, initial load diameter, and variations of the nested array configuration on the K-shell output. Nominally, optimized configurations have been identified, with optimization determined by the highest K-shell output with the fastest rising, narrowest x-ray pulse. In this paper, the results of experiments performed to evaluate additional load configuration variations such as increased radial anode-cathode (RAK) gap, increases in wire number on nested arrays, and orientation of the nested arrays are presented. For stainless steel wire arrays (K-shell emission ~6.7 keV), increasing the wire number on the nested arrays resulted in increased K-shell yield and K-shell power. Increasing the RAK gap from 6 mm to 10 mm resulted in changes to both the soft x-ray emission and stainless steel K-shell emission. The orientation of the wires on the inner and outer arrays of copper (8.4 keV) wire arrays was not observed to impact the radiated output, although calculations suggest that the effect of wire orientation will be overwhelmed by magnetic field asymmetries induced by the wire location relative to the openings in the return current can.

I. INTRODUCTION

Wire array experiments performed over the last few years at the 20 MA Z Accelerator have studied a wide range of K-shell x-ray sources, including aluminum (Al, 1.7 keV), titanium (Ti 4.7 keV), stainless steel (SS, 6.7 keV), and copper (Cu, 8.4 keV) [1-4]. These experiments have identified load configurations in which the K-shell radiation is optimized for the highest yield with the fastest rising, narrowest x-ray pulse. The optimized configurations are summarized in Table 1. All the configurations utilized a 2:1 outer:inner mass and diameter ratio, and produced 1.0-1.3 MJ of total radiation. These loads generally have low wire numbers relative to the inertial confinement fusion loads typically fielded at Z [5], with interwire gaps (IWG) up to 3 mm. For the nested configurations, this raises concerns about the transparency of the inner array to the imploding outer

Table 1: Summary of optimized K-shell load configurations at Z

Material	Outer array dia. (mm)	Load mass (mg)	K-shell energy (kJ)	K-shell FWHM (ns)
Al	40	3.05	~400	7
Ti	50	2.5	~100	7
SS	55	2.15	~50	3
Cu	60	2.0	~20	4

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14. ABSTRACT
A variety of wire array experiments the last few years at the 20 MA Z Accelerator have been performed to assess the impact of initial load mass, initial load diameter, and variations of the nested array configuration on the K-shell output. Nominally, optimized configurations have been identified, with optimization determined by the highest Kshell output with the fastest rising, narrowest x-ray pulse. In this paper, the results of experiments performed to evaluate additional load configuration variations such as increased radial anode-cathode (RAK) gap, increases in wire number on nested arrays, and orientation of the nested arrays are presented. For stainless steel wire arrays (K-shell emission ~6.7 keV), increasing the wire number on the nested arrays resulted in increased K-shell yield and K-shell power. Increasing the RAK gap from 6 mm to 10 mm resulted in changes to both the soft x-ray emission and stainless steel K-shell emission. The orientation of the wires on the inner and outer arrays of copper (8.4 keV) wire arrays was not observed to impact the radiated output, although calculations suggest that the effect of wire orientation will be overwhelmed by magnetic field asymmetries induced by the wire location relative to the openings in the return current can.

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array material. Altering the orientation ("clocking") of the outer array wires relative to the inner array wires can alter this transparency and the interaction of the inner and outer material. Changes in the dynamics of the imploding mass could impact the radiated output. The large IWG could also be limiting the radiated output, as previous experiments with single wire arrays [6-9] have shown significant improvements in total output by decreasing the spacing between adjacent wires. It is unclear if this effect applies in the same fashion to nested configurations or to K-shell emission, however. Experiments with tungsten arrays have found that closure of the radial anode-cathode (RAK) gap may be reducing the radiated output achieved by shunting current from the load region [10]. The optimized loads in Table 1 all utilized RAK gaps scaled using a classical scaling from a 40 mm diameter array with a 5 mm RAK gap. In this Proceedings paper, the results of experiments to study the effects of increased wire number of nested arrays (section II), the orientation of the outer wires relative to the inner wires (section III), and a variation in the RAK gap (section IV) are presented. The wire number experiment and RAK gap experiment were performed with SS arrays, and the "clocking" experiment was performed with Cu arrays. Stagnated plasma conditions from these experiments are discussed and compared with the conditions observed from previous experiments. Computational results for the "clocking" configuration are also be presented.

II. WIRE NUMBER VARIATION OF NESTED ARRAYS

Previous wire number studies with z pinches have shown that smaller interwire gap wire array loads lead to enhanced powers resulting from faster rising, narrower x-ray pulses [6-9]. All of these experiments were performed with single arrays, with both tungsten (W) [6,9] and Al [7,8] arrays. For the Al arrays, the K-shell emission was generally unaffected by the change in wire number, however, although the K-shell power generally increased due to improvements in the x-ray pulseshape similar to that observed with the total x rays. In the experiments described here, nested SS wire arrays were fielded to assess both the impact of wire number on a nested configuration, and the impact on the measured K-shell energy. All the loads fielded utilized the 55 mm on 27.5 mm nested configuration, with a 2:1 outer:inner mass ratio. The total mass of the array was similar for all the arrays (see Table 1), to ensure similar peak current for each configuration. The IWG was decreased from 1.66 mm to 0.9 mm by changing the number and size of the wires used. The total measured output behaved as expected, with the total power increasing to ~ 185 TW for

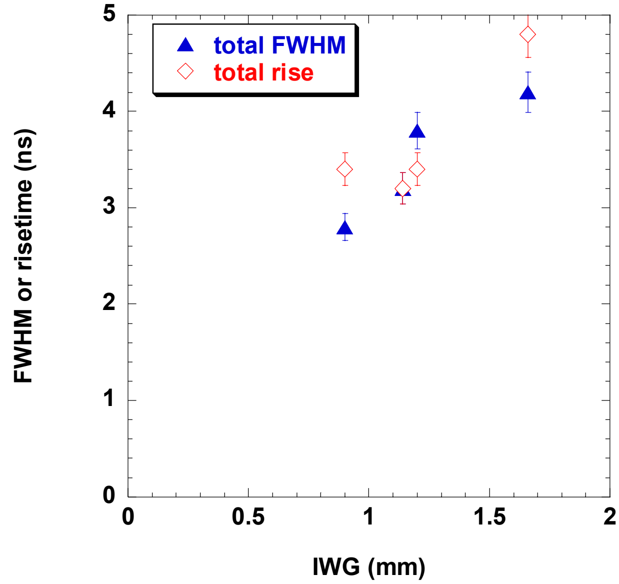

Figure 1: Full-width-at-half-maximum and risetime of total x-ray emission as a function of IWG for 55 mm nested SS wire arrays.

the smallest IWG fielded (0.9 mm), a noticeable increase over the ~ 165 TW measured for the typical 55mm SS configuration (IWG of 1.66 mm). The total radiated yield was similar, with the improved power resulting from a faster, narrower x-ray pulse, as observed previously. The general belief is that this improved power results from a reduction in the growth of the Rayleigh Taylor instability (RT), as evidenced by the faster risetime of the x-ray pulse [11]. The variation of pulseshape with IWG for the total x-rays is illustrated in Figure 1, where the full-width-at-half-maximum (FWHM) and risetime of the x-ay pulse are plotted. For the total x rays, a decrease in both FWHM and risetime is observed as the IWG decreases. Table 2 summarizes the variations in radiated output observed for the different IWG fielded. The radiated K-shell energy increases with the decreased IWG, while reductions in both the FWHM and risetime are also observed. The pulseshape improvements observed (illustrated in Figure 2) are similar to those seen for the total x-ray pulse. The increased K-shell yield with

Table 2: Summary of measured output for 55 mm nested SS loads with different IWG

IWG (mm)	K-shell yield (kJ)	K-shell risetime (ns)	K-shell FWHM (ns)	T_e (keV)	N_i (cm^{-3})
1.66	40.5	2.7	4.2	3.6	9×10^{19}
1.2	44.2	2.1	3.5	na	na
1.14	49.1	2.1	2.8	4.2	1.5×10^{20}
0.9	53	1.5	2.4	4.1	1.8×10^{20}

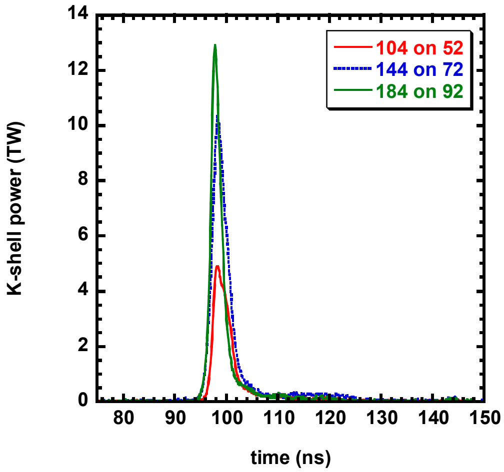

Figure 2: The peak K-shell power improved for higher wire number arrays (smaller IWG).

smaller IWG has not been previously observed. For these large diameter K-shell loads at Z, this improved K-shell output could very likely be the result of reductions in RT growth that allow for more uniform emission of K-shell from the pinch; plasma conditions necessary for the K-shell emission are generally not observed globally in the radiating pinch [2,3]. Table 2 also lists the electron temperature (T_e) and ion density (N_i) inferred from measured time-integrated K-shell spectra using the method described in Ref. 12. T_e showed noticeable improvement with reduced IWG, as did N_i, which is strongly tied to K-shell emission and tends to affect the output more significantly than changes in temperature. Time-resolved pinhole images also showed tighter, more uniformly irradiating regions at peak output. These observations are consistent with the assertion of a reduction in the RT growth. Note that all loads were fielded at least twice, with the values presented representing typical measured values.

III. CLOCKING OF NESTED WIRE ARRAYS

As previously discussed, the orientation ("clocking") of the outer wires relative to the inner wires on a low wire number nested array can impact the transparency of the inner array and the interaction of the inner and outer array material. This can lead to a change in the implosion of the wire array and the resulting radiated output. The typical nested configuration fielded for Cu wire arrays at Z (see Table 1) uses twice as many wires on the outer array than are present on the inner array, e.g., 80 on 40 wires. The outer and inner arrays are usually aligned such that each inner wire lines up with an outer wire, which leaves half of the outer wires to pass unobstructed through to the axis of the wire array. This typical configuration would suggest approximately 50% transparency of the inner array to outer material.

To study the effect of the transparency on the stagnated pinch, two additional configurations were fielded with the standard 60 mm nested Cu wire array. In these configurations, the same number of wires was fielded on both the inner and outer arrays (40 on 40), with the wires aligned ("clocked", nominally 0% transparent) and not aligned ("anti-clocked", nominally 100% transparent). The mass ratio between the outer and inner arrays remained the same as the standard array, with twice as much mass on the outer as the inner. This was accomplished by using larger diameter wires on the outer array than were used on the inner array. Pre-test calculations using Gorgon [13] suggested that the precursor would be indistinguishable with the "clocked" and "anti-clocked" configurations, although the current switch to the inner array would be different for the two cases; i.e., for the "clocked" case, the current switch resembles a flux compression case, whereas for the "anti-clock" case, a very sudden switch of current to the inner array occurs when the outer material approaches the inner array.

Results of the experiments are shown in Figure 3, which clearly shows that the total and K-shell radiated output were very similar for all three configurations. No obvious effect of the outer and inner wire orientation was observed. The "clocked" and "anti-clocked" cases had a significantly different x-ray pulseshape for the K-shell emission than the typical configuration, however, with a distinct double-peak observed. As a result, the radiated power was significantly lower for the "clocked" and "anti-clocked" cases than observed for the standard array. This structure was the same for both the "clocked" and "anti-clocked" cases, which suggested that the altered

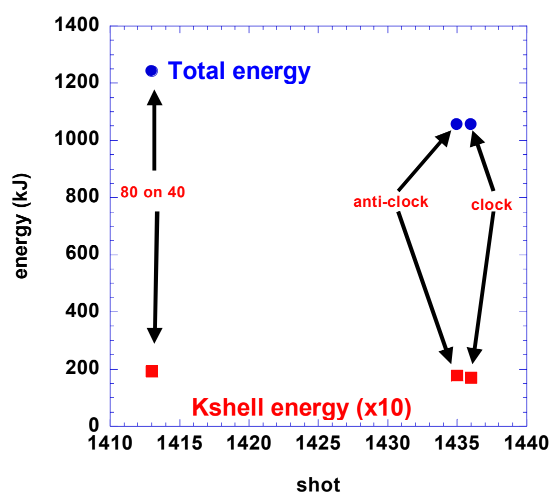

Figure 3: Total and K-shell energy (x 10) radiated from the three different nested Cu wire array configurations.

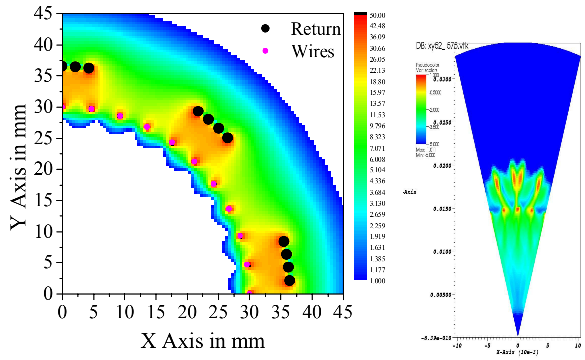

Figure 4: Gorgon modeling of the "anti-clocked" configuration shows that a magnetic field asymmetry resulting from the proximity of the wires to the return can affects the mass flow of the outer wire array.

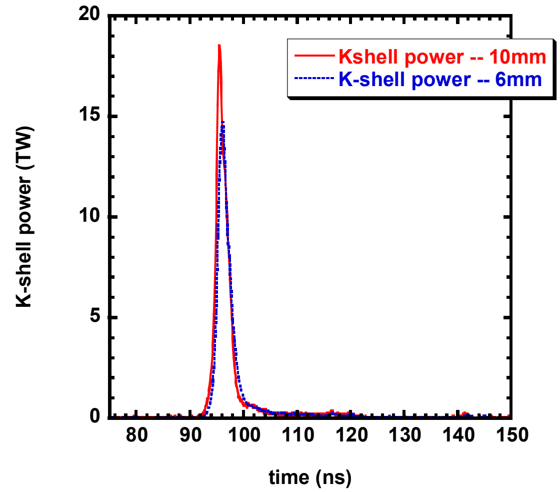

Figure 5: K-shell power waveforms for 55 mm nested SS arrays (184 on 92 wires) for the 6mm and 10 mm RAK gap cases.

pulseshape was likely the result from the different dynamics associated with the large IWG imposed on the outer wire array rather than the clocking configuration itself. Pinhole images of the K-shell and soft (277 eV) x-rays [14] for the standard vs. "clocked" and "anti-clocked" cases show similar pinch diameters, although the standard case has more uniform irradiation in the K-shell along the length of the pinch.

Post-shot calculations have suggested that there may be another explanation for observations with the different outer:inner wire orientations. Gorgon modeling of the implosion, shown in Figure 4, suggests that a magnetic field asymmetry associated with the return current can could be dominating the early phase of the implosion. The wires in close proximity to the material of the return current can experience a different magnetic field than those wires which fall in the areas of the slots of the return current can. The wires opposite the wall material see slightly higher currents than their counterparts opposite the slots, which results in a faster ablation rate. This material starts streaming toward the axis earlier than material from the other wires. The higher current also leads to a field asymmetry, which results in focusing of the mass during the implosion. This produces a similar interaction between outer and inner array materials for both the "clocked" and "anti-clocked" cases. Changing the RAK gap should alter the magnetic field structure experienced by the outer wires, which could impact both the implosion and the radiated output.

IV. INCREASED RAK GAP

Previous work has shown that the size of the RAK gap can significantly impact the pinch dynamics and radiated output from wire arrays at Z [10]. Given these results, and the results from section III, an experiment was performed in which the RAK gap was increased for the high wire number SS wire array previously fielded at Z (see Table 2). The standard RAK gap for the 55 mm nested configuration is 6mm; for this comparison, the RAK was increased to 10 mm. The peak current delivered to both loads was similar for both cases, approximately 19 MA. The radiated K-shell power, shown in Figure 5, shows a slight improvement for the larger RAK gap load. A similar improvement was observed for the total radiated power. The increased power results from a combination of a slightly faster, narrower x-ray pulse, and a slight increase in measured yield. The pulseshape differences are within the normal spread of data when shots are fielded multiple times (see figure 6, for example), and the improvements are generally consistent with the previously reported observations of Ref. 10.

Comparison of the energy radiated in the main x-ray pulse, obtained by examining the peak power * FWHM, indicates that gap closure was not a factor in these experiments, however. The fraction of total energy in the main x-ray pulse ranged from 0.6 to 0.8 for the 6 mm RAK, but increased only to 0.85 for the 10 mm RAK. This would suggest that the fraction of energy in the late time radiation decreased only slightly for the 10 mm RAK gap configuration. Similarly, the fraction of the K-shell energy radiated in the main x-ray pulse ranged from 0.45 to 0.6 for the 6 mm RAK, and remained within this range (0.58) for the 10 mm RAK. Again, this indicates that the fraction of K-shell energy radiated late in time was unchanged with the larger RAK. These results suggest that increasing the RAK gap did not reduce the level of gap closure that was likely present in the configuration, as additional current that would have been delivered by delaying or reducing the gap closure should have resulted in higher radiated output later in time. One possible explanation for the slight increase in yield observed (and the improved power illustrated in Figure 5) is a change in the magnetic field experienced by the outer array due to the increased RAK gap, as described in Section III for the

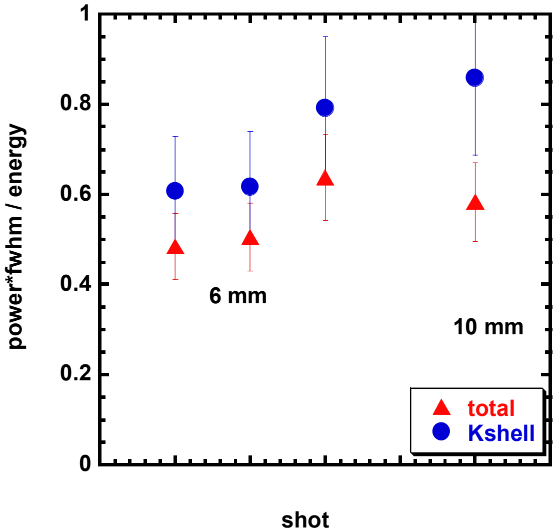

Figure 6: Fraction of total (triangle) and K-shell (circle) energy in the main x-ray pulse for the 6mm and 10 mm RAK gaps.

Cu wire array. Further experiments are necessary before a definitive conclusion can be presented, however.

V. SUMMARY

In this Proceedings, the results of experiments to study the impact of reduced IWG, orientation of outer and inner wires, and the RAK gap on total and K-shell x-ray emission have been described. Higher wire number loads resulted in improved total and K-shell power, through improvements in the radiated pulseshape; this result is similar to that previously observed with single arrays. An enhancement of the SS K-shell yield was also observed, the first such observation for a K-shell source. The faster risetime indicates that these improvements likely result from reductions in the RT instability growth, which can lead to higher temperature and density plasmas. The improved plasma conditions are particularly advantageous for K-shell sources at Z, which require high temperatures and densities for copious K-shell emission. Future wire number variations utilizing advanced imaging would help quantify the mechanisms responsible for the improved output.

Experiments were also performed with nested Cu arrays to assess the impact of the orientation of the outer and inner wires on the stagnated pinch. Calculations had suggested that the current switching should change, which could alter the implosion dynamics, but in experiments comparing the standard configuration to "clocked" and "anti-clocked" configurations, little difference was observed, other than in pulseshape. The measured pulseshapes were similar for the "clocked" and "anti-clocked" cases, but represented a substantial degradation from the standard load. The pulseshape for the "clocked" and "anti-clocked" cases had a double-peak structure, with powers less than half of that measured for the standard configuration. It is possible that the low wire number used (large IWG) on the outer array could have impacted the performance of the array. Additionally, post-shot calculations suggest that the dominant physics for these configurations is a magnetic field asymmetry introduced by the proximity of the return can to the outer array wires.

Experiments to increase the RAK gap to alter this field, as well as assess the general impact of RAK gap on the radiated output, illustrate that this magnetic field asymmetry is potentially impacting the implosion of nested SS arrays. Increasing the RAK gap for the nested SS arrays resulted in slightly higher radiated yields, although the pulseshapes did not change significantly. The radiated power was enhanced for both the total and K-shell emission with the larger RAK gap. Examination of the fraction of energy emitted in the main x-ray pulse suggests that increasing the RAK gap did not alter any gap closure effects that might be present, as evidenced by essentially no change in the fraction of radiation emitted after the main x-ray pulse. It is possible that the enhanced power (and yield) observed for the larger RAK results from the change in the magnetic field that develops between the outer array wires and the return current can. Additional experiments could help address this effect further through a more complete study of the RAK gap, as well as alternate can configurations that could induce other magnetic field asymmetries with a constant RAK gap.

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